



# The Effect of Magnetohydrodynamic (MHD) Energy Bypass on Specific Thrust for a Supersonic Turbojet Engine

*Theresa L. Benyo*  
*Glenn Research Center, Cleveland, Ohio*

## NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA STI Help Desk at 443-757-5803
- Telephone the NASA STI Help Desk at 443-757-5802
- Write to:  
NASA Center for AeroSpace Information (CASI)  
7115 Standard Drive  
Hanover, MD 21076-1320



# The Effect of Magnetohydrodynamic (MHD) Energy Bypass on Specific Thrust for a Supersonic Turbojet Engine

*Theresa L. Benyo*  
Glenn Research Center, Cleveland, Ohio

Prepared for the  
48th Aerospace Sciences Meeting  
sponsored by the American Institute of Aeronautics and Astronautics  
Orlando, Florida, January 4–7, 2010

National Aeronautics and  
Space Administration

Glenn Research Center  
Cleveland, Ohio 44135

## Acknowledgments

Theresa L. Benyo thanks Dr. Isaiah Blankson and Dr. Steve Schneider of NASA Glenn Research Center for their guidance and encouragement throughout this research.

This report contains preliminary findings,  
subject to revision as analysis proceeds.

This work was sponsored by the Fundamental Aeronautics Program  
at the NASA Glenn Research Center.

*Level of Review:* This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information  
7115 Standard Drive  
Hanover, MD 21076-1320

National Technical Information Service  
5301 Shawnee Road  
Alexandria, VA 22312

Available electronically at <http://gltrs.grc.nasa.gov>

# The Effect of Magnetohydrodynamic (MHD) Energy Bypass on Specific Thrust for a Supersonic Turbojet Engine

Theresa L. Benyo

National Aeronautics and Space Administration

Glenn Research Center

Cleveland, Ohio 44135

## Abstract

This paper describes the preliminary results of a thermodynamic cycle analysis of a supersonic turbojet engine with a magnetohydrodynamic (MHD) energy bypass system that explores a wide range of MHD enthalpy extraction parameters. Through the analysis described here, it is shown that applying a magnetic field to a flow path in the Mach 2.0 to 3.5 range can increase the specific thrust of the turbojet engine up to as much as 420 N/(kg/s) provided that the magnitude of the magnetic field is in the range of 1 to 5 Tesla. The MHD energy bypass can also increase the operating Mach number range for a supersonic turbojet engine into the hypersonic flight regime. In this case, the Mach number range is shown to be extended to Mach 7.0.

## Nomenclature

$A_e$	cross sectional area of the nozzle exit
$A_g$	cross sectional area of the MHD generator
$B$	magnetic field intensity
$C_p$	constant pressure specific heat
$F$	thrust
$F/\dot{m}_a$	specific thrust
$f$	fuel-to-air mass flow ratio
$K$	Faraday loading parameter
$L$	length of the MHD generator
$\dot{m}_a$	mass flow rate of the air at the entry of the MHD generator
$M_a$	flight Mach number
$p_a$	freestream static pressure
$p_e$	static pressure at the nozzle exit
$P_{elec}$	power output of the MHD generator
$q_f$	fuel heating value
$R$	gas constant for air
$T_{0,3}$	stagnation temperature at entrance to the burner
$T_{0,4}$	stagnation temperature at the exit of the burner
$T_{0,5}$	stagnation temperature at the exit of the turbine
$T_{0,6}$	stagnation temperature at the exit of the MHD accelerator
$T_{0,a}$	freestream total temperature
$T_{0,lim}$	stagnation temperature limit of the engine
$T_a$	freestream static temperature
$u$	flow velocity
$\gamma$	specific heat ratio for air
$\eta_c$	combustion efficiency
$\eta_{N(a)}$	enthalpy extraction/addition ratio of the MHD accelerator
$\eta_{N(g)}$	enthalpy extraction/addition ratio of the MHD generator

$\eta_{s(a)}$	isentropic efficiency for the MHD accelerator
$\eta_{s(g)}$	isentropic efficiency for the MHD generator
$\pi_a$	stagnation pressure ratio of the MHD accelerator
$\pi_b$	stagnation pressure ratio of the burner
$\pi_c$	stagnation pressure ratio of the compressor
$\pi_d$	stagnation pressure ratio of the diffuser
$\pi_e$	stagnation pressure ratio of the expansion section
$\pi_g$	stagnation pressure ratio of the MHD generator
$\pi_n$	stagnation pressure ratio of the nozzle
$\pi_p$	stagnation pressure ratio of the pre-ionizer
$\pi_t$	stagnation pressure ratio of the turbine
$\Pi$	global stagnation pressure ratio
$\sigma$	electrical conductivity
$\chi$	fraction of generator power diverted to pre-ionizer

## Introduction

A 1-D thermodynamic cycle analysis (Ref. 1) was completed for a supersonic turbojet engine with a MHD energy bypass system which consists of a MHD generator and MHD accelerator for flow control and energy bypass capability. For many years, MHD technology has been studied and recognized as a viable technology for increasing the performance of supersonic and hypersonic flight vehicles. Electromagnetic fields are used to enhance flow features in supersonic/hypersonic inlets for flow control and combustor energy bypass. Expanding flows in high speed nozzles may also be accelerated by means of electromagnetic forces to augment the thrust generated. The overall objective of this paper is to establish the feasibility and demonstrability of a kinetic energy bypass from the inlet air-stream of a jet engine that has been weakly ionized by an external means to a downstream location using MHD interaction with the ionized air stream.

This paper describes a previous 1-D thermodynamic cycle analysis (Ref. 2) of a ramjet/scramjet and describes an extension of this analysis to a turbojet by exploring a range of MHD enthalpy extraction parameters using a previous (Ref. 3) enthalpy extraction/addition ratio derivation. It should be noted that these results are preliminary and require further study. The analysis is a point-to-point 1-D thermodynamic cycle analysis where only energy bypass is considered. This analysis additionally does not take into consideration any variable cross sectional areas. The Mach 3.3 condition at the J-102 inlet needs to be maintained at the higher free-stream Mach numbers. Maintaining these constraints would normally require an iterative procedure, which this analysis does not have. Even so, this analysis produces results that are encouraging enough to continue to explore the use of MHD bypass for supersonic and hypersonic flight.

## Background

A 1-D thermodynamic cycle analysis previously completed (Ref. 2) was studied and the results were verified. The analysis assumes a constant stagnation pressure ratio for each element of the MHD energy bypass ramjet/scramjet engine which is illustrated in Figure 1. The MHD energy bypass system incorporated into a conventional gas turbine technology is a revolutionary concept which offers three distinct advantages. It allows turbomachinery to operate continuously over the entire range of Mach 0 to 7 where no deadweight engines are carried aloft. This revolutionary concept only uses hydrocarbon fuel where the plasma in the weakly ionized flow may be used to reform the hydrocarbon fuel into hydrogen. And finally, there is high potential for increased specific impulse.

A MHD energy bypass system bypasses kinetic energy from the inlet stream and uses it downstream to generate more thrust or reduce drag on the vehicle. This energy bypass is accomplished by using weak ionization of the inlet stream by an external means and MHD interaction with the ionized gas. The key

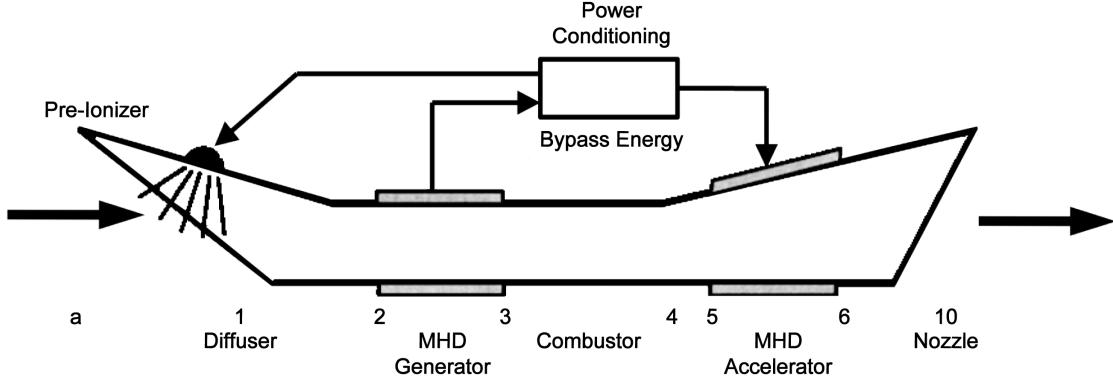


Figure 1.—Airbreathing hypersonic engine with MHD energy bypass system. Reference stations and process names are indicated.

feature of the engine lies in the additional hardware surrounding the jet engine. There are three main components of a MHD energy bypass system; the pre-ionizer, the MHD generator and the MHD accelerator.

The pre-ionizer is positioned in the inlet where it ionizes the incoming flow which, in conjunction with applying a magnetic field to the flow, provides the benefits of flow control. The flow is ionized by the high voltage nanosecond discharge method (Ref. 4) where high-voltage, short pulse duration, high pulse repetition rate discharges generate ionization in supersonic cold flows ( $T_0 = 300$  K).

The MHD generator towards the front of the engine acts as a flow control device and provides power to the pre-ionizer and MHD accelerator. The electromagnetic fields produced by the MHD generator are used to enable variable inlet flow control that is similar to that controlled by variable geometry. The MHD generator is a non-obstructing means of total temperature reduction that can be controlled by applied magnetic fields and load parameter adjustment. The MHD accelerator at the back of the engine accelerates the flow exiting the engine by applying electromagnetic forces to ionized flow which work together to augment the thrust generated.

In order to fully understand the current work described in this paper, it is essential to document the equations used in the previous analyses. The specific thrust of an engine can be derived by coupling the first and second laws of thermodynamics with elementary gasdynamic relationships. The calculation for the specific thrust ( $F/\dot{m}_a$ ) as derived in Reference 1 is

$$\frac{F}{\dot{m}_a} = \left[ (1 + f) \sqrt{\frac{2\gamma RT_{0,6}(\Pi-1)}{(\gamma-1)\Pi}} - M_a \sqrt{\gamma RT_a} \right] + \frac{p_e A_e}{\dot{m}_a} \left( 1 - \frac{p_a}{p_e} \right) \quad (1)$$

Notice that as long as the ratio of  $p_a/p_e$  is 1, the additive term contributes nothing to the specific thrust calculation. Two main contributors to the specific thrust calculation are the fuel-to-air mass flow rate ( $f$ ) and the freestream Mach number, ( $M_a$ ). In Equation (1),  $f$  is the fuel-to-air mass flow rate and is further expressed as

$$f = \frac{1 - (T_{0,3}/T_{0,lim})}{(\eta_c q_f / C_p T_{0,lim}) - 1} \quad (2)$$

Another important contributor to Equation (1) is the global stagnation pressure ratio. This ratio takes into account the pressure ratios of the pre-ionizer, the diffuser, the MHD generator, the burner, the expansion, the MHD accelerator and the nozzle. The global stagnation pressure ratio parameter is further expressed as

$$\Pi = \left(1 + \frac{\gamma+1}{2} M_a^2\right) \left(\pi_p \pi_d \pi_g \pi_b \pi_e \pi_a \pi_n \frac{p_a}{p_e}\right)^{(\gamma-1)/\gamma} \quad (3)$$

where the individual stagnation pressure ratios of each component are either computed using efficiency parameters or held at constant values. The pressure ratios of particular interest in this analysis are the pressure ratios for the MHD generator and MHD accelerator. The stagnation pressure ratio for the MHD generator is

$$\pi_g = \left(1 - \frac{\eta_{N(g)}}{\eta_{S(g)}}\right)^{\frac{\gamma}{\gamma-1}} \quad (4)$$

and the stagnation pressure ratio for the MHD accelerator is

$$\pi_a = \left[1 + \eta_{S(a)} \left(\frac{1}{1+f}\right) \frac{(1-\chi)\eta_{N(g)} T_{0,a}}{1-\chi\eta_{N(g)} T_{0,4}}\right]^{\frac{\gamma}{\gamma-1}} \quad (5)$$

The analysis studied produces results indicated in Figure 2 wherein the enthalpy extraction parameter of the MHD generator was held constant at five different levels; 0, 0.25, 0.5, 0.65, and 0.75. This parameter is the ratio of the stagnation enthalpy change in the MHD generator device to the entrance stagnation enthalpy. For each parameter level, the specific thrust was calculated for all Mach numbers from 1 to 12. As indicated in the figure, as the MHD generator enthalpy extraction increases, the operating range of the engine expands into Mach numbers above Mach 8. For example, if one wants to fly at Mach 8, the MHD generator enthalpy extraction percentage would have to be at least 25 percent. In order to fly at Mach 10, a MHD generator enthalpy extraction percentage of at least 50 percent is required. It is noted however, that the maximum specific thrust achieved is decreased as a result of using the MHD energy bypass system. Even though the analysis shows a maximum potential performance decrease, with the application of the MHD energy bypass system (i.e., creating an environment where the MHD generator enthalpy can be changed), the aircraft has the potential of operating at higher Mach

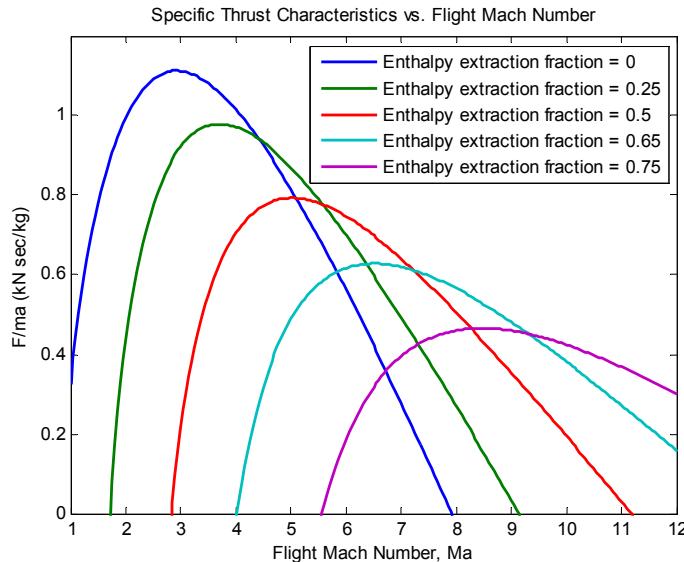


Figure 2.—Results of 1-D thermodynamic cycle analysis for a ramjet/scramjet from Litchford et al. with added  $\eta_{N(g)}$  values of 0.65 and 0.75. Specific thrust as a function of flight Mach number for  $\eta_{N(g)} = 0, 0.25, 0.5, 0.65$ , and  $0.75$ .

numbers. Therefore, the result of the analysis indicates that there are flight envelope benefits and should be researched more vigorously.

As derived in Reference 2, the enthalpy extraction/addition ratio is determined by the output power produced by the MHD generator and the enthalpy input through the ‘inlet’ of the MHD generator. This ratio is portrayed in the following equation:

$$\eta_{N(g)} = \frac{P_{elec}}{\dot{m}_a C_p T_{0,a}} \quad (6)$$

where  $P_{elec}$  is the power output of the MHD generator (in Watts) and  $T_{0,a}$  is the total temperature of the freestream air and  $\dot{m}_a$  is the mass flow rate of the air coming into the MHD generator. Equation (6) allows a calculation of a variable MHD generator enthalpy extraction parameter. The expression for the power output,  $P_{elec}$  also derived in Reference 2 was used to calculate the power output of the MHD generator. That equation is expressed as:

$$P_{elec} = \sigma u^2 B^2 K (1 - K) A_g L \quad (7)$$

where  $\sigma$  is the conductivity of the ionized air,  $u$  is the velocity of flow entering the MHD generator in m/s,  $B$  is the applied magnetic field in Tesla,  $K$  is the Faraday loading parameter (usually held at 0.5) for the generator,  $A_g$  is the cross sectional area of the MHD generator in  $\text{m}^2$ , and  $L$  is the length of the generator in meters.

## Current Analysis with a Turbojet

This analysis builds upon previous work performed (Ref. 2) with a ramjet/scramjet and uses a variable MHD generator enthalpy extraction parameter coupling details of the MHD generator design into the analysis (Ref. 3) to further enhance a thermodynamic cycle analysis of a supersonic turbojet engine. The MHD generator is used to augment turbojet performance mainly by extending the operating range to higher Mach numbers.

The geometry used for this analysis is shown in Figures 3 and 4. The concept engine is a MHD driven energy bypass supersonic turbojet engine (Ref. 5). The MHD generator may be employed in the inlet, nozzle, and another duct, individually and in combination. The possibility of electromagnetically extracting part of the turbojet inlet air kinetic energy is the key feature. The concept potentially offers variable inlet

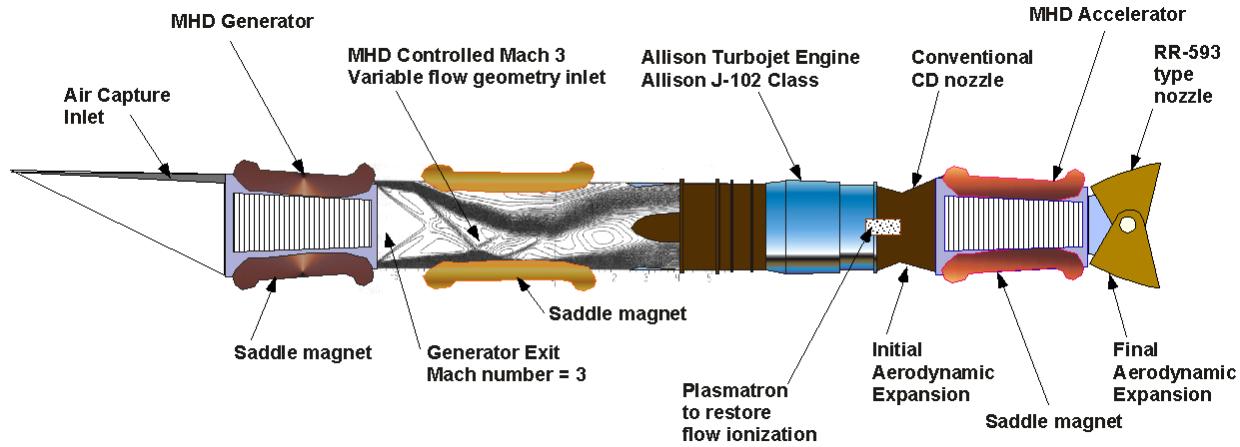


Figure 3.—General arrangement of MHD controlled turbojet for high-speed propulsion.

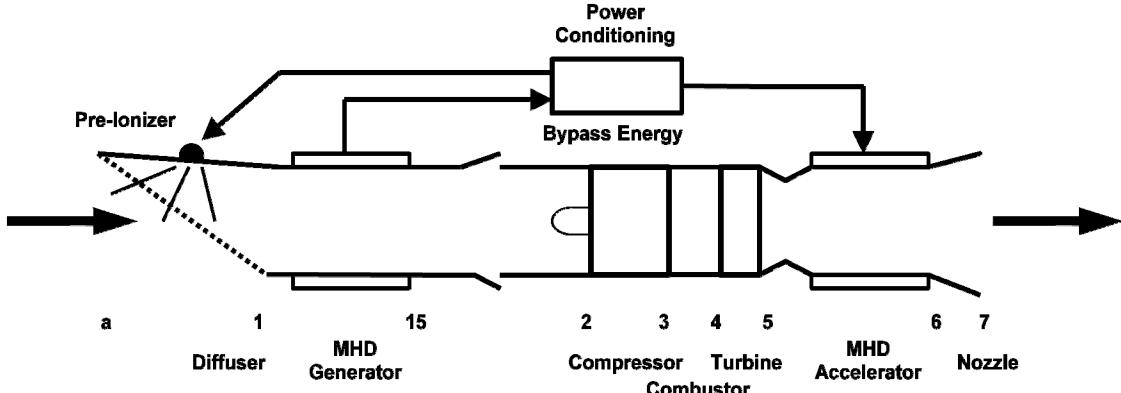


Figure 4.—Schematic of MHD controlled turbojet for high-speed propulsion.

geometry performance without the complexity of moving inlet parts. Three primary aeropropulsion purposes are served by the concept. Firstly, the flow enthalpy into the combustor is reduced allowing more efficient addition of energy in the combustor without exceeding temperature limitations on the turbine materials. Secondly, the applied electromagnetic fields and their body forces can enhance off-design performance by manipulating the flow features in the supersonic/hypersonic inlets thereby reducing total pressure losses and entropy changes for the same level of flow compression by other means. Thirdly, electrical power removed can be used for various on-board vehicle requirements including plasma flow control around the vehicle. In addition, the expanding flow in the high-speed nozzle may also be augmented by electromagnetic forces to generate more thrust.

Because a supersonic turbojet engine is being used in this case instead of a ramjet/scramjet, a different expression for the global stagnation pressure ratio is needed. Equation (8) expresses the new global stagnation pressure ratio.

$$\Pi = \left( 1 + \frac{\gamma+1}{2} M_a^2 \right) \left( \pi_p \pi_d \pi_g \pi_c \pi_b \pi_t \pi_e \pi_a \pi_n \frac{p_a}{p_e} \right)^{(\gamma+1)/\gamma} \quad (8)$$

where two additional stagnation pressure ratios are needed to model the supersonic turbojet's compressor and turbine. The stagnation pressure ratio of the compressor in this case is held constant at a well-known value. The turbine's stagnation pressure ratio is computed in the normal manner and expressed as:

$$\pi_t = \left[ \frac{1 - \left( 1 - \frac{T_{0,5}}{T_{0,4}} \right)}{\eta_t} \right]^{\gamma} \quad (9)$$

In addition, because of the turbine, a new stagnation pressure ratio of the MHD accelerator was needed. The equation used for this pressure ratio is:

$$\pi_a = \left( 1 + \eta_{s(a)} \eta_{N(a)} \right)^{\gamma} \quad (10)$$

where the efficiency parameter for the MHD accelerator is computed by the following equation:

$$\eta_{N(a)} = \frac{T_{0,6} - T_{0,5}}{T_{0,5}} \quad (11)$$

In this study, the focus was on a supersonic turbojet engine like the Allison J-102 with a MHD energy bypass system and the following operating conditions (Refs. 6 and 7):

### **System**

Stagnation temperature limit ( $T_{0,lim}$ ): 1600, 1800, 2000, and 2200 K

Freestream temperature ( $T_a$ ): 233 K

Turbojet engine length: about 1.2 m

### **Pre-ionizer**

Stagnation pressure ratio ( $\pi_p$ ): 1

### **Diffuser**

Stagnation pressure ratio ( $\pi_d$ ): 0.7

### **MHD Generator**

Mass flow rate of air ( $\dot{m}_a$ ): 28 kg/s

Electrical conductivity ( $\sigma$ ): 1 mhos/m and 10 mhos/m

Magnetic field ( $B$ ): varies from 0 to 20 Tesla

Length ( $L$ ): 1 and 10 m

Cross sectional area ( $A_g$ ): 0.5 m<sup>2</sup>

Isentropic efficiency: 0.9

Fraction of generator power diverted to pre-ionizer ( $\chi_p$ ): 0.05

Faraday loading parameter ( $K$ ): 0.5

### **Compressor**

Isentropic efficiency: 0.77

Stagnation pressure ratio ( $\pi_c$ ): 12

### **Combustor**

Combustion efficiency ( $\eta_c$ ): 1

Fuel heating value ( $q_f$ ): 45,000 kJ/kg

### **Turbine**

Isentropic efficiency: 0.79

Stagnation pressure ratio ( $\pi_t$ ): varies to match compressor power

### **Expansion**

Stagnation pressure ratio ( $\pi_e$ ): 1

### **MHD Accelerator**

Isentropic efficiency: 0.9

### **Nozzle**

Stagnation pressure ratio ( $\pi_n$ ): 0.98

## **Results for a Turbojet**

For this study, the specific thrust was calculated for a range of Mach numbers from 1 to 7. The MHD generator's enthalpy extraction ratio varied with a magnetic field range of 0 to 20 Tesla. Figures 5 to 12

show the results at four combustion temperature limits (1600, 1800, 2000, and 2200 K), two MHD lengths (1 and 10 m), and two conductivity levels (1 and 10 mhos/m).

The data in Figures 5 and 6 are for a 1600 K temperature limit. Note that there is no specific thrust benefit with the application of magnetic fields below Mach 2. The application of magnetic fields enables positive specific thrust from Mach 3 to 5.

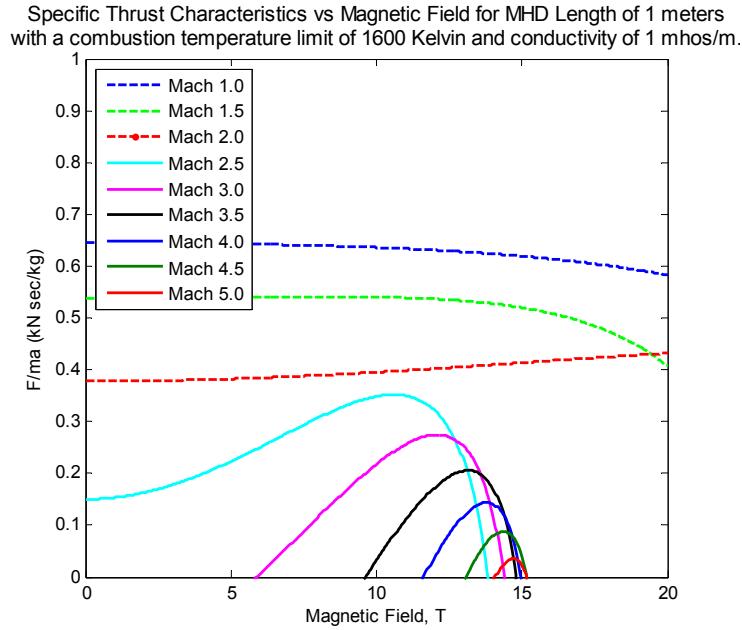


Figure 5.—Results of 1-D thermodynamic cycle analysis for a turbojet.  
Specific thrust as a function of magnetic field for variable  $\eta_{N(g)}$ .

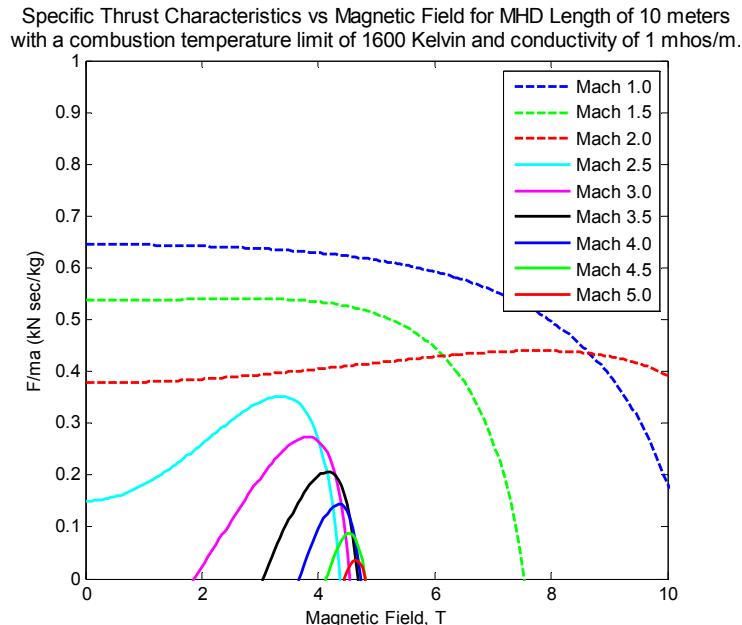


Figure 6.—Results of 1-D thermodynamic cycle analysis for a turbojet.  
Specific thrust as a function of magnetic field for variable  $\eta_{N(g)}$ .  
Results are the same if the MHD generator length is 1 m and conductivity of the flow field is 10 mhos/m.

In the data shown in Figure 5, a high magnetic field of over 7 Tesla is required for any specific thrust benefit to be realized with a low combustion temperature limit of 1600 K, a moderate flow conductivity of 1 mhos/m, and a MHD generator length of 1 m. If either the flow conductivity or the MHD generator length increases by tenfold, the required magnetic field drops by a factor of three as shown in Figure 6. An increase of 202 N/(kg/s) at a magnetic field of 3 Tesla is realized at the Mach 2.5 level. This corresponds to a thrust increase of 5.7 kN at a 28 kg/s flow rate at Mach 2.5. This affords a fairly good increase in performance of a supersonic turbojet engine.

If we allow the combustion temperature limit to increase to levels of 1800, 2000, and 2200 K; higher Mach number flight is enabled. We can potentially increase the operating range into the hypersonic flight regime by using MHD energy bypass.

Figures 7 and 8 show results with a combustion temperature limit of 1800 K. Note again that there is no specific thrust benefit with the application of magnetic fields below Mach 2. The application of magnetic fields in this case enables positive specific thrust up to Mach 6. If either the length of the MHD generator or flow conductivity is increased by tenfold, the required applied magnetic field decreases again by a factor of three. As seen in Figure 8, the specific thrust is increased by 144 N/(kg/s) at the Mach 2.5 level with an applied magnetic field of 3 Tesla. Even better, the specific thrust is increased by 337 N/(kg/s) at Mach 3.0 with an applied magnetic field of about 3.75 Tesla. This corresponds to a thrust increase of 4.0 and 9.4 kN respectively at a 28 kg/s flow rate.

If we increase the combustion temperature limit to 2000 K, even better results are achieved and are shown in Figures 9 and 10. The possible Mach numbers that show specific thrust improvements are now up into the Mach 6.5 range. As indicated in Figure 10 at Mach 2.5, the specific thrust is shown to increase by 106 N/(kg/s) with an applied magnetic field of just under 3 Tesla. Similarly, an increase in specific thrust of 263 N/(kg/s) is realized at Mach 3.0 with a magnetic field of about 3.5 Tesla. This corresponds to a thrust increase of 2.9 and 7.4 kN respectively at a 28 kg/s flow rate.

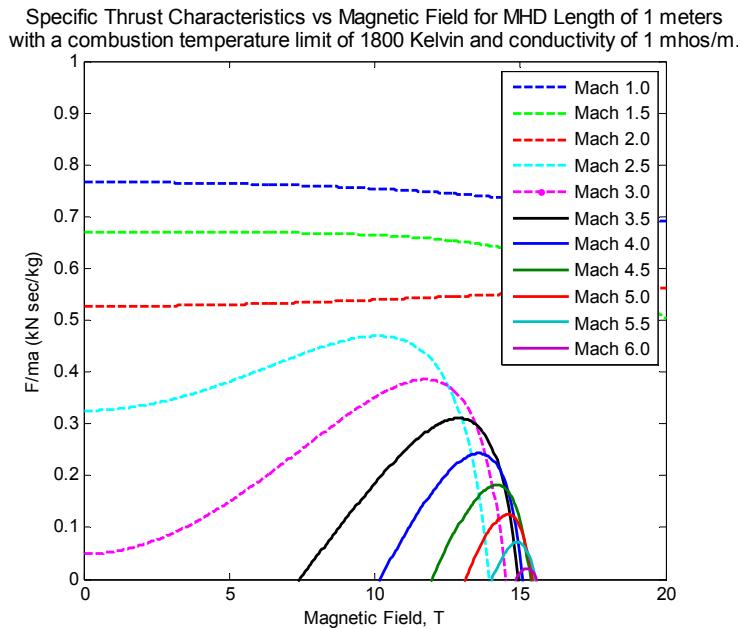


Figure 7.—Results of 1-D thermodynamic cycle analysis for a turbojet.  
Specific thrust as a function of magnetic field for variable  $\eta_{N(g)}$ .

Specific Thrust Characteristics vs Magnetic Field for MHD Length of 10 meters with a combustion temperature limit of 1800 Kelvin and conductivity of 1 mhos/m.

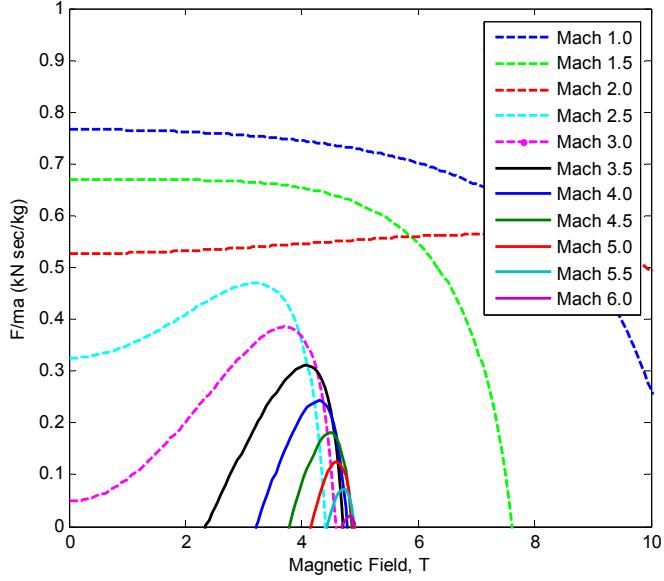


Figure 8.—Results of 1-D thermodynamic cycle analysis for a turbojet. Specific thrust as a function of magnetic field for variable  $\eta_{N(g)}$ . The results are the same if the MHD generator length is 1 m and the conductivity of the flow field is 10 mhos/m.

Specific Thrust Characteristics vs Magnetic Field for MHD Length of 1 meters with a combustion temperature limit of 2000 Kelvin and conductivity of 1 mhos/m.

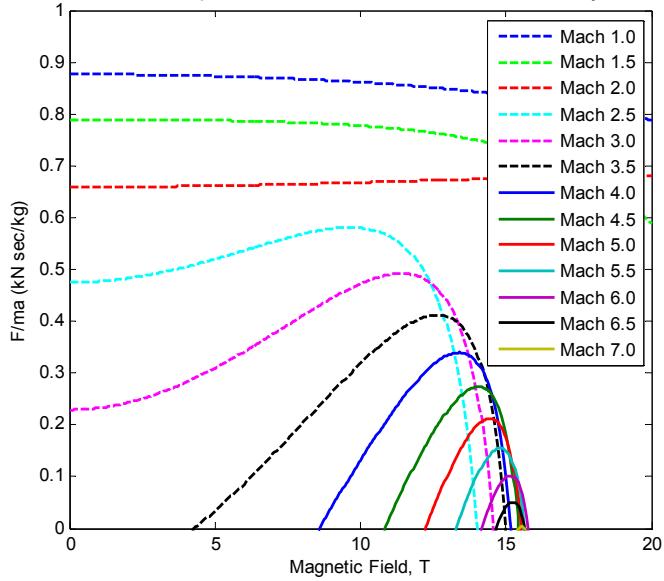


Figure 9.—Results of 1-D thermodynamic cycle analysis for a turbojet. Specific thrust as a function of magnetic field for variable  $\eta_{N(g)}$ .

The final two figures (Figs. 11 and 12) show results with a combustion temperature limit of 2200 K. At this temperature limit, the range of possible Mach numbers further increases to Mach 7. Along with the wider Mach number range, an increased specific thrust is now realized between Mach numbers 2 to 3.5. Figure 12 shows that at the Mach 2.5 level, the specific thrust increases by 79 N/(kg/s) with a magnetic field of about 2.5 Tesla. A larger increase in performance occurs at the Mach 3.0 level where

the specific thrust grows by 213 N/(kg/s) with an applied magnetic field of around 3.75 Tesla. Still larger specific thrust can be found at Mach 3.5 where a 420 N/(kg/s) increase can be realized with a magnetic field of just below 4 Tesla. This corresponds to a thrust increase of 2.2, 5.9 and 11.8 kN respectively at a flow rate of 28 kg/s.

Specific Thrust Characteristics vs Magnetic Field for MHD Length of 10 meters with a combustion temperature limit of 2000 Kelvin and conductivity of 1 mhos/m.

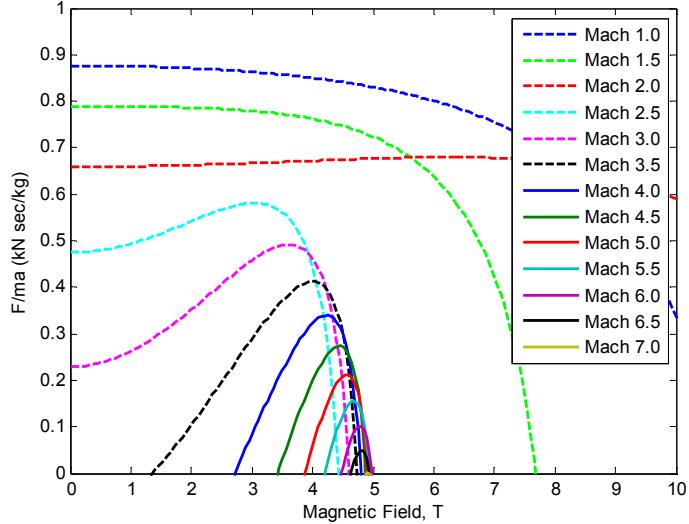


Figure 10.—Results of 1-D thermodynamic cycle analysis for a turbojet. Specific thrust as a function of magnetic field for variable  $\eta_{N(g)}$ . The results are the same if the MHD generator length is 1 m and the conductivity of the flow field is 10 mhos/m.

Specific Thrust Characteristics vs Magnetic Field for MHD Length of 1 meters with a combustion temperature limit of 2200 Kelvin and conductivity of 1 mhos/m.

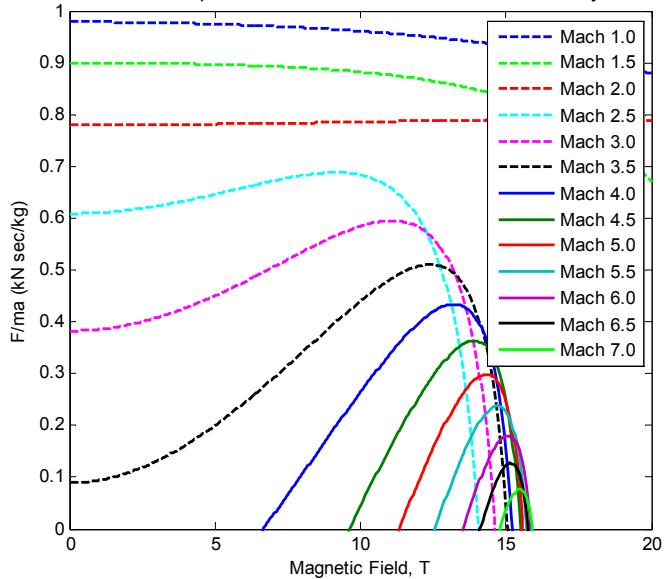


Figure 11.—Results of 1-D thermodynamic cycle analysis for a turbojet. Specific thrust as a function of magnetic field for variable  $\eta_{N(g)}$ .

Specific Thrust Characteristics vs Magnetic Field for MHD Length of 10 meters with a combustion temperature limit of 2200 Kelvin and conductivity of 1 mhos/m.

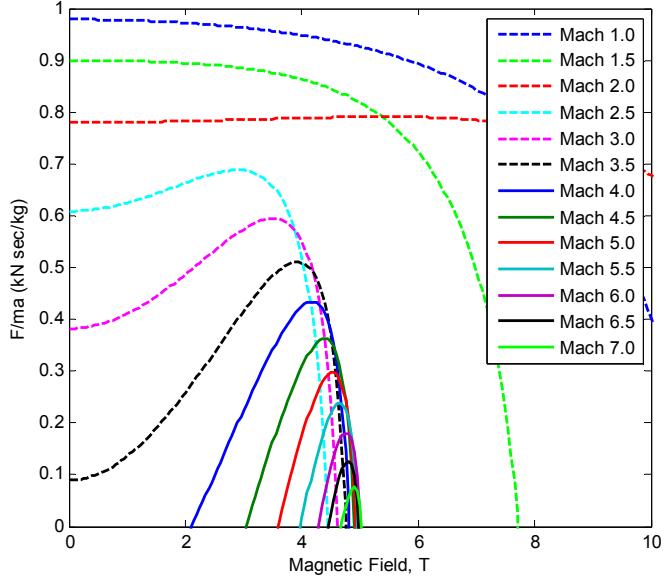


Figure 12.—Results of 1-D thermodynamic cycle analysis for a turbojet. Specific thrust as a function of magnetic field for variable  $\eta_{N(g)}$ . The results are the same is the MHD generator length is 1 m and the conductivity of the flow field is 10 mhos/m.

## Conclusion

Through the new analysis described here, it is shown that applying a magnetic field to a supersonic flow path in the Mach 2 to 3.5 range will increase the specific thrust up to 420 N/(kg/s). It also shows that by using a MHD energy bypass system, a supersonic aircraft's operating envelope may be increased into the hypersonic flight regime. All this is shown with a magnetic field between 1 to 5 Tesla and the length of the MHD generator between 1 and 10 m.

As evidenced by the above results, MHD technology is a valuable addition to supersonic and hypersonic flight and should be studied further and in progressively more detail. As it stands, this analysis has shown that better specific thrust performance can be realized for an operating range of Mach 2 to Mach 3.5 and that there is high potential for an expanded operating envelope up to Mach 7.0 provided that suitable conditions are present and allow the supersonic turbojet to operate at combustion temperatures of 2200 K. In addition, it is hoped that future work can discover the conditions necessary for the required magnetic field to be in the more desired range of 1 to 2 Tesla.

By working the areas listed above, it is desired that MHD technology can fully make its way into high-speed flight and reap the following benefits of this technology.

- The flow enthalpy into the combustor is reduced allowing more efficient addition of energy in the combustor without exceeding temperature limitations on the turbine materials.
- The applied electromagnetic fields and their body forces can enhance off-design performance by manipulating the flow features in the supersonic/hypersonic inlets thereby reducing total pressure losses, and entropy changes for the same level of flow compression by other means.
- The electrical power removed can be used for various on-board vehicle requirements including plasma flow control around the vehicle. In addition, the expanding flow in the high speed nozzle may also be augmented by the electromagnetic forces to generate more thrust.

This analysis also confirmed previous work completed by Litchford, et al. as evidenced by the figures showing the expanded Mach number range that is possible.

## Future Plans

It is planned to conduct cycle analyses to properly match the flows between the pre-ionizer, the MHD generator, the turbojet engine and the MHD accelerator and to establish the operating conditions for a jet engine cycle that are optimal for kinetic energy transfer from inlet air to a downstream location in the engine. It is also desired to establish a model for a jet engine with MHD energy bypass and determine the design and operating conditions in which the thrust-to-weight ratio, thrust per unit mass of fuel consumption, and effectiveness of energy utilization are maximized.

Specific future work in this area of full engine cycle analyses using MHD technology includes:

- Establish the operating conditions for a turbo-jet engine cycle, that are optimal for kinetic energy transfer from inlet air (Mach reduction to 0.8) to a downstream location in the engine in a bypass mode.
- Establish the interaction parameter and efficiency for MHD conversion of kinetic energy of the ionized gas to electrical energy.
- Quasi 1-D MHD theory will be employed to conduct inlet analysis evaluations using experimentally determined conductivity, interaction parameters, and the mass flow captured at the inlet.
- Conduct interfacing studies between the MHD bypass generator, the turbojet engine, and the MHD accelerator. Perform a thermal analysis to properly match the flows from an inlet employing an MHD generator to a supersonic turbojet engine such as the Allison J-102 engine. Working with various operating conditions (such as flow mass, magnetic field, combustion temperature limit, and length of the MHD generator and accelerator) should help accomplish flow matching and extend operation to higher Mach numbers before performance degradation occurs.

## References

1. Hill, P.G., C.R. Peterson, "Mechanics and Thermodynamics of Propulsion," Addison-Wesley Publishing Co., Inc., 1965.
2. Litchford, R.J., J.W. Cole, V.A. Bityurin, and J.T. Lineberry, "Thermodynamic Cycle Analysis of Magnetohydrodynamic-Bypass Hypersonic Airbreathing Engine," NASA/TP—2000-210387.
3. Murthy, S.N.B and I.M. Blankson, "MHD Energy Bypass Turbojet-Based Engines," presented at the 51<sup>st</sup> International Astronautical Congress, October 2000, Rio de Janeiro, Brazil, IAF-00-5-5-05.
4. Nishihara, M., J.W. Rich, W.R. Lempert, and I.V. Adamovich, "Low-temperature M=3 Flow Deceleration by Lorentz Force," *Phys. Fluids* **18**, 086101 (2006).
5. Schneider, S.J, I.M. Blankson, I.V. Adamovich, and J.W. Rich, "Magnetogasdynamics Inlet Power Extraction for a Gas Turbine," presented at the 34<sup>th</sup> AIAA Plasmadynamics and Lasers Conference, June 2003, AIAA-2003-4289.
6. Blankson, I.M., S. Schneider, "Hypersonic Engine using MHD Energy Bypass with a Conventional Turbojet," presented at the 12<sup>th</sup> AIAA International Space Planes and Hypersonic Systems and Technologies, December 2003, AIAA-2003-6922.
7. J-102 packet includes engine specifications and engine performance envelope from Isaiah Blankson.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>				
1. REPORT DATE (DD-MM-YYYY) 01-12-2010	2. REPORT TYPE Technical Memorandum	3. DATES COVERED (From - To)		
<b>4. TITLE AND SUBTITLE</b> The Effect of Magnetohydrodynamic (MHD) Energy Bypass on Specific Thrust for a Supersonic Turbojet Engine			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
<b>6. AUTHOR(S)</b> Benyo, Theresa, L.			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER WBS 599489.02.07.03.07.02.04; 599489.02.07.03.04.03.01	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> E-17311	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> National Aeronautics and Space Administration Washington, DC 20546-0001			<b>10. SPONSORING/MONITOR'S ACRONYM(S)</b> NASA	
			<b>11. SPONSORING/MONITORING REPORT NUMBER</b> NASA/TM-2010-216734	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Unclassified-Unlimited Subject Category: 07 Available electronically at <a href="http://gltrs.grc.nasa.gov">http://gltrs.grc.nasa.gov</a> This publication is available from the NASA Center for AeroSpace Information, 443-757-5802				
<b>13. SUPPLEMENTARY NOTES</b>				
<b>14. ABSTRACT</b> This paper describes the preliminary results of a thermodynamic cycle analysis of a supersonic turbojet engine with a magnetohydrodynamic (MHD) energy bypass system that explores a wide range of MHD enthalpy extraction parameters. Through the analysis described here, it is shown that applying a magnetic field to a flow path in the Mach 2.0 to 3.5 range can increase the specific thrust of the turbojet engine up to as much as 420 N/(kg/s) provided that the magnitude of the magnetic field is in the range of 1 to 5 Tesla. The MHD energy bypass can also increase the operating Mach number range for a supersonic turbojet engine into the hypersonic flight regime. In this case, the Mach number range is shown to be extended to Mach 7.0.				
<b>15. SUBJECT TERMS</b> Magnetohydrodynamic simulation; Thermodynamics; Jet thrust; Supersonic turbojet				
16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 19	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email: <a href="mailto:help@sti.nasa.gov">help@sti.nasa.gov</a> )
a. REPORT U	b. ABSTRACT U			c. THIS PAGE U



